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Improving the bearing fault diagnosis efficiency by the adaptive stochastic resonance in a new nonlinear system

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ABSTRACT

It is a challenging task to detect the weak character signal in the noisy background. The stochastic resonance (SR) method has been wildly adopted recently because it can not only reduce the noise, but also enhance the weak feature information simultaneously. However, the traditional bistable model for SR is not perfect. So, this paper presents a new model with periodic potential to induce the adaptive SR. In the new model, based on the adaptive SR theory, the system parameters are simultaneously optimized by the improved artificial fish swarm algorithm. Meanwhile, the improved signal-to-noise ratio (ISNR) is set as the evaluation index. When the ISNR reaches a maximum, the output is optimal. In order to eliminate interference to obtain more useful information, the signals are preprocessed by Hilbert transform and High-pass filter before being input to the adaptive SR system. To verify the effectiveness of the proposed method, both numerical simulation and the vibration signal of the rolling element bearing from the lab experimental are adopted. Both of the results indicate that the adaptive SR model proposed shows better performance in weak character signals detection than the traditional adaptive SR in the bistable model. Meanwhile, the experimental signals with different working conditions are also processed by the new method. The results show that the method proposed could be more widely applied.

1. Introduction

In modern mechanical industry, the rolling element bearings are widely used. They are prone to suffer various faults such as inner ring fault, out ring fault, cage train fault and rolling elements fault due to work in a harsh working environment [1]. The rolling element bearing fault signal can be described as a weak periodic impact signal with certain frequency. The fault signals are usually weak and submerged in the noisy background which increases the difficulty of fault identification. Therefore, how to realize weak character signals detection from the noisy background has become the research hotspot. The traditional methods [2–7] such as empirical mode decomposition (EMD), wavelets transform (WT) and their improved forms are widely used to deal with the noise. They all show good performance. However, the feature information is weakened when the noise is removed. So, the way to remove the noise is not optimal.

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The SR method proposed by Benzi et al. [8] is a new method which is different from the traditional denoising methods. It has a specify mechanism that transferring the noise energy to the weak feature information. The weak feature information could be enhanced while the noise is reduced. Afterwards, application of SR in the engineering field has been researched thoroughly and widely applied to mechanical fault diagnosis. In the respect of the large parameter signal procession, Tan et al. [9] proposed a frequency-shifted and re-scaling stochastic resonance method to make up for the deficiency of the existing large parameter stochastic resonance. Similarly, He et al. [10–12] combined multiscale noise tuning with traditional SR to enhance the signal-to-noise ratio (SNR) of the system output. Then, an improved multiscale noise tuning of SR is applied to the multiple transient faults in rolling element bearings. In the respect of the differential equation establishment, Li et al. [13] proposed the second-order enhanced SR. Lai et al. [14,15] did research on the two-dimensional Duffing oscillator and demonstrated the feasibility with the practical examples. In the respect of the potential function model, the tristable potential [16,17], Woods–Saxon potential [18], pinning potential [19] and step-varying asymmetric [20] are proposed. Moreover, the SR may also occur in linear systems [21–24]. However, the linear models of SR cannot be applied in the field of fault diagnosis. In the linear models, there is one or more coupled terms when the SR appearing. The coupled terms may origin from the parametric excitation or the coupling of the signal and noise. In the respect of the adaptive SR, Lei et al. [25], Chen et al. [26] and Liu et al. [27] did some works with different optimization algorithm and processing steps. All of them applied the proposed method into the planetary gearbox fault diagnosis and achieved good results by full use of optimal SR. Beside, to enhance detection performance of the SR, an adaptive cascaded SR was proposed by Lei et al. [28] and a time delayed feedback SR was proposed by Lu et al. [29].

From the works above, it can be found that the research object of the most researchers is the adaptive stochastic resonance in the bistable system (BSR). The research on other effective nonlinear models is less. So, in this paper, we pay more attention to the potential function and an adaptive stochastic resonance in the periodic potential system (PSR) is presented. For the SR in the periodic potential system, some researchers have done interesting works. Fronzoni and Mannella [30] studied the motion of a particle in a periodic potential plus a bias, driven by a noise and a coherent forcing. Nicolis [31] extended the classical setting of stochastic resonance to account for the presence of intermediate states. Saikia et al. [32,33] considered the underdamped motion of a particle in a periodic potential. In their research, two cases of the system that the friction coefficient is different are studied. Yang and Liu [34] made the theoretical investigation on vibrational resonance in a periodic potential system by the method of direct separation of motions. Liu and Jin [35] studied the motion of an underdamped Brownian particle in a periodic potential subject to a harmonic excitation and a colored noise. However, due to the difficulty in the analytical analysis, almost all of them are focused on the numerical investigations. In order to extend its application range, the method proposed in this paper is applied into the field of mechanical fault diagnosis. In our study, the signal is in high-frequency and the noise is strong. In other words, the adiabatic approximation condition is not satisfied. It results in the hard difficulty in treating the problem by analytical method. Moreover, in the fault diagnosis filed, the numerical study is much more popular than the analytical investigation. As a result, we will study the problem mainly by the numerical analysis.

The specific arrangements of this paper are as follows. In Section 2, the parameter-induced PSR is introduced. In Section 3, the adaptive PSR method based on the improved artificial fish swarm algorithm is established. Then, the bearing fault simulation signal is used to verify the effectiveness of the adaptive PSR. Meanwhile, the adaptive BSR is made as a comparison. In Section 4, the proposed method is used to deal with the bearing fault experimental signals. In order to test the robustness of the proposed method, the signals with different working conditions are also used. Finally, the main results of this paper are briefly described in Section 5.

2. Parameter-induced PSR

2.1. Theory of PSR

According to the previous works [36,37], it can be known that the SR can be described as a signal with noise and a nonlinear system match well with each other. Then a phenomenon occurs that the signal is enhanced and the noise is weakened. The SR phenomenon can be expressed by the dimensionless Langevin equation, which is governed by

$$\begin{cases} \frac{\mathrm{d}y}{\mathrm{d}t} = -\frac{\mathrm{d}U(y)}{\mathrm{d}y} + s(t) + n(t) \\ \langle n(t) \rangle = 0 \\ \langle n(t)n(t') \rangle = 2D\delta(t-t') \end{cases} \tag{1}$$

in which $s(t)$ is the input signal, $n(t)$ is the Gaussian white noise with intensity D and $U(y)$ is the nonlinear potential function.

For the bistable potential system, $U(y)$ is a reflection-symmetric quartic potential

$$U(y) = U_b(y) = -\frac{1}{2}ay^2 + \frac{1}{4}by^4 \tag{2}$$

where a and b are the barrier parameters with positive real values.

In terms of the periodic potential system, $U(y)$ can be described as